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JET TRANSPORT REJECTED TAKEOFFS

DAVID W. OSTROWSKI

FEBRUARY 1977

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Flight Standards Service
Washington, D.C. 20591

Technical Report Documentation Page

1. Report No. AFS-160-77-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Jet Transport Rejected Takeoffs		5. Report Date: Feb[redacted]977
		6. Performing Organization Code: AFS-160
7. Author(s): David W. Ostrowski		8. Performing Organization Report No.
9. Performing Organization Name and Address: Flight Standards Service, Federal Aviation Administration, 800 Independence Avenue, S.W., Washington, D.C. 20591		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered: Final Report
		14. Sponsoring Agency Code: 27 P.
15. Supplementary Notes		

14 6 11 10 9 12

16. Abstract

Jet transport airplane rejected takeoffs (RTO's) at heavy weights and high speeds and RTO accidents/incidents involving tires, wheels, and brakes have prompted an assessment of RTO test procedures and the system by which RTO accountability is achieved for day-to-day operations. It is concluded that 3 to 4% of air carrier accidents, fatalities, and aircraft losses can be attributed to tire/wheel/brake related RTO's. Tire failures and the lack of accountability for the increased accelerate-stop distance required on wet/slippery runways are significant factors. Recommendations are made for reducing the incidence of tire failures and accounting for the increased accelerate-stop distance necessitated by wet/slippery runways.

17. Key Words: Jet transport rejected takeoff, Aborted Takeoff, Wet/Slippery Runway, Tires, Wheels, Brakes, Tire failures, Test procedures	18. Distribution Statement: Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	23	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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PREFACE

This report presents an analysis of tire/wheel/brake related rejected takeoff accidents and test procedures. Recommendations are made for reducing the incidence of tire failures and accounting for the increased accelerate-stop distance necessitated by wet/slippery runways.

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1. INTRODUCTION

The trend among jet transport aircraft toward heavier takeoff weights and higher takeoff speeds has tended to aggravate an already critical situation, the rejected takeoff. Although inherent hazards in the rejected takeoff (RTO) have been somewhat alleviated by improvements in braking systems, extended runway lengths, and, in the case of wet runways, by runway grooving, the takeoff energy levels generated by modern jet transport airplanes continue to make the rejected takeoff a critical operation. This, along with a number of RTO accidents and incidents, has prompted the FAA to review the present procedures by which RTO's are tested and the system by which RTO accountability is achieved for day-to-day operations.

2. OBJECTIVE

The objective of this effort is to review RTO test procedures and RTO accident/incident data and to develop improved procedures if warranted. This effort involving RTO's is a portion of an overall action to assess aircraft tire, wheel, and brake failures and recommend action to minimize their causes.

3. DISCUSSION

a. RTO Perspective

It is appropriate to begin with putting the rejected takeoff in perspective relative to jet transport operations. In rejecting a takeoff, for whatever reason, the operation then becomes similiar to a landing after touchdown in that all effort is devoted to bringing the aircraft to a safe stop on the remaining runway. For this reason RTO's can best be put in proper perspective by comparison with landings. Although similar to a landing with regard to the mechanics involved after touchdown and much less frequent in occurrence, the RTO generally is more critical than the landing in terms of bringing the airplane to a safe stop. This is due to the following factors:

(1) RTO's usually occur at higher airplane gross weights.
(2) RTO's often occur at higher speeds.
(3) By the time a problem is recognized, the decision made to abort the takeoff, and abort action is initiated, there is usually much less runway available in which to bring the airplane to a safe stop.

(4) Most tire failures (an estimated 75%) occur during takeoff with relatively few in landing. Tire failure can, in fact, cause the takeoff to be rejected and can initiate a series of events which significantly reduce the stopping capability of the airplane at a time when it is most needed. This will be explored in more depth later in the analysis.

(5) Regulations governing jet transport rejected takeoffs do not contain the additional safety factors required for landings. For landings on dry surfaces, FAR 121.195 requires that jet transports be capable of stopping on 60% of the available effective runway. For wet runway landings the available runway length must be 115% of the dry landing distance. For takeoffs on dry runways, FAR 25.113 requires the greater of the actual distance needed to a height of 35 feet with an engine out at V_1 or 115% of the actual distance needed to a height of 35 feet with all engines operating. Unlike landings, no additional safety margins are included in the regulations for takeoffs on wet runways.

One policy tends to alleviate the critical nature of RTO's. The use of reverse thrust is usually not permitted in RTO testing and is not included in the airplane flight manual accelerate-stop data used for planning takeoffs. Thus if a takeoff must be aborted, additional deceleration capability (in the form of reverse thrust) is usually available to provide some margin of safety. In order to keep the comparison of RTO's and landings in perspective, it should be noted that reverse thrust is not used in landing tests nor included in the flight manual landing data either.

b. RTO Accident/Incident/Maintenance Report Analysis

In analyzing RTO's, data were accumulated from several sources including National Transportation Safety Board Accident Reports, FAA accident, incident and maintenance reports, and United Kingdom Civil Aeronautics Authority accident reports. During this analysis 171 RTO's resulting in accidents, incidents, or subsequent repair from 1964 through mid-1976 were assessed. Although, some earlier and foreign records were not readily available, this analysis represents a reasonably thorough assessment of the significant jet transport RTO accidents and incidents with regard to flight testing procedures and criteria.

c. Tire/Wheel/Brake Involvement
Of the 171 RTO's analyzed, 149 had some tire, wheel, or brake involvement, i.e., failures or malfunctions in these areas caused or were a contributing factor in initiating the RTO.

d. Tire Involvement
Of the 149 cases of tire, wheel, or brake involvement, tire failures were by far the major cause or factor in RTO's accounting for 124 of these cases. This significant proportion of tire failures warrants special attention. Tires are an especially critical element in jet transport RTO's as will be discussed later.

e. Wet/Slippery Runway Involvement
Not all the RTO data analyzed contained indications as to runway conditions; however, some concept of the degree of wet/slippery runway involvement can be gained from the fact that wet or slippery runway conditions existed in 8 of the 29 RTO accidents/incidents assessed from National Transportation Safety Board data sources for 1964 through 1974. More significant, however, is the fact that wet or slippery runways were involved in 3 of the 8 RTO accidents which resulted in fatalities or total destruction of the aircraft. Three of these eight RTO accidents can be omitted from any discussion concerning tire, wheel, or brake involvement, so that 3 out of the 5 RTO accidents with tire, wheel, or brake involvement and fatalities or aircraft destruction also involved wet or slippery runways. These RTO accidents will be summarized later in this discussion.

f. Wet/Slippery Runway RTO Certification and Operation
In certifying transport aircraft for the rejected takeoff condition, several actual RTO's are performed up to the maximum braking energy to which the airplane is to be certified. The usual procedure followed is to accelerate the airplane to V_1, or the test speed, cut the critical engine to simulate an engine failure, apply brakes, reduce the power on the remaining engines to idle, and extend spoilers. The airplane must be brought to a safe stop on the runway. Small fires are permissible provided they are confined to tires, wheels, and brakes, would not result in progressive engulfment of the aircraft during passenger/crew evacuation, and do not require suppression for five minutes after the stop. Reverse thrust is not used in

certification tests or accounted for in the Airplane Flight Manual stopping distance charts in order to provide a margin of safety for operations. Should it then become necessary to reject a takeoff, reverse thrust would normally be used. RTO certification tests and most airplane flight manual stopping distance charts are based on dry runway stopping distances only. Time delays are included in stopping distance charts in airplane flight manuals to account for recognition of failures and pilot reaction time.

g. Major RTO Accidents:

As noted previously, of the 171 RTO accidents/incidents studied in this analysis, eight resulted in fatalities or total destruction of the aircraft. These are especially significant and warrant further amplification.

(1) Three of these eight, although classified as RTO's, are not pertinent to this tire/wheel/brake analysis and can be eliminated from this discussion because they involved improper procedures or failures in which no reasonable amount of improved RTO capability could have prevented the accident. For information they are:

AIRCRAFT	DATE	PLACE	REMARKS
727	3/21/68	Chicago	Improper flap setting, warning horn sounded, takeoff roll was continued but aborted after liftoff, aircraft collided with ditches and was destroyed.
CV-880	6/24/69	Moses Lake, Washington	Simulated engine failure during initial climb, delayed corrective action, failed to maintain control and crashed. 3 fatalities, 2 serious injuries, aircraft destroyed.

AIRCRAFT	DATE	PLACE	REMARKS
DC-8	10/16/69	Stockton, California	False ground spoiler position indication, takeoff aborted, collided with dirt bank, aircraft destroyed.

(2) Tire/Wheel/Brake Related RTO Accidents Involving Fatalities of Total Aircraft Destruction:

AIRCRAFT	DATE	PLACE	REMARKS
707	11/23/64	Rome	Engine failure, takeoff aborted below V_1, reverse thrust selected but #2 reverser failure permitted asymmetrical thrust, ran off end of wet runway, struck pavement roller and burned, 50 fatalities, 17 serious injuries, aircraft destroyed.
707	11/6/67	Erlanger, Kentucky	Crew heard loud noise when passing another aircraft mired in mud near the runway, suspected collision with other aircraft and aborted takeoff beyond V_1, aircraft ran off end of runway, broke apart, caught fire and was destroyed, one passenger died 4 days later.

AIRCRAFT	DATE	PLACE	REMARKS
DC-8	11/27/70	Anchorage, Alaska	Attempted takeoff on ice covered runway in freezing drizzle. Poor acceleration as a result of failure of all main wheels to rotate went undetected by crew until after V_1 was attained, aircraft was rotated but did not become airborne and went off end of runway at high speed, broke apart, and was destroyed by fire, 47 fatalities, 49 serious injuries. The cause of the wheel lockup was undetermined.
747	6/11/75	Bombay, India	392 passengers and crew on board, blown tires on takeoff, wheel fire, rejected takeoff, application of foam hindered by exhaust from running engines, passengers and crew evacuated, aircraft destroyed by fire.
DC-10	11/12/75	Jamaica, N.Y. (JFK Int'l.)	Birds ingested and fire developed in No. 3 engine during takeoff, takeoff rejected well below V_1 on wet runway, tires blew, reverse thrust on 2 engines used, aircraft ran off end of runway and was destroyed by fire. Passengers and crew evacuated.

h. Analysis of Major RTO Accidents:

These five major Tire/Wheel/Brake related RTO accidents contain several of the factors commonly found in RTO accidents, i.e.,blown tires with resultant loss of braking capability, wet or slippery runways, and unavailability of full reverse thrust.

(1) Tire Failures:

Blown tires played a significant role in the accidents of the 747 at Bombay and the DC-10 at JFK International. In the 747 accident, blown tires caused the takeoff to be rejected. This accident also illustrates another hazard involving post RTO fires: that of getting enough foam on the fire in a timely fashion and keeping it suppressed. In this case, proper application of foam was hampered by the fact that the engines were not shut down, and it can be argued that the airplane might have been saved if proper procedures were followed. On the other hand, it can also be argued that the entire unfortunate series of events would not have occurred had the tires not failed. Fire suppression was a significant factor in the loss of the DC-10 at JFK International. There are indications that the fire was suppressed initially, but due to the large amount of burning fuel in the area, the foam supply ran out and the fire flared up again, destroying the aircraft. It can be argued that the destruction of this aircraft could have been prevented had sufficient foam been available; however, both this and the Bombay case are real situations faced by the airlines in daily operations. The important point in the DC-10 accident with respect to tires is that the blown tires contributed to reduced braking capability which permitted the airplane to run off the end of the runway. In this particular case there apparently was no significant damage due to leaving the runway, but such is not always the case as illustrated by the 707 accident at Erlanger, Kentucky, and the DC-8 accident at Anchorage, Alaska, in which the aircraft broke apart in rough terrain after leaving the runway. The DC-8 was also difficult for fire and rescue crews to reach, another inherent danger in RTO accidents in which the aircraft leaves the runway.

(2) Wet/Slippery Runways:

Of the major RTO accidents, wet or slippery runways were significant factors in the destruction of the 707 at Rome, the DC-8 at Anchorage, and the DC-10 at JFK International. It is especially significant to note that both the 707 and DC-10 aborted the takeoff below V_1 in accordance with current criteria, yet the

wet conditions permitted both aircraft to skid off the end of the runway. In the case of the DC-8 at Anchorage, the coefficient of friction on the ice-covered runway was so low as to permit the aircraft to travel most of the length of the 10,900 ft. runway with locked wheels before it became apparent to the crew that a problem existed. This is an extreme example of how braking action can be reduced to almost nothing.

(3) Unavailability of Full Reverse Thrust:

The 707 accident at Rome and the DC-10 accident at JFK International are examples of the unavailability of full reverse thrust which can occur during an RTO. The reduction of reverse thrust in the 707 was due to a mechanical failure in a reverser, and an engine failure. The reduced reverse thrust in the DC-10 was a result of an engine failure, one of the major causes of RTO's and, therefore, a significant consideration in assessing RTO's.

i. RTO Accident Comparison and Significance

(1) In assessing the significance of Tire/Wheel/Brake related RTO accidents in relation to the total U.S. air carrier accidents from all causes, the following data has been compiled from NTSB and FAA sources:

TABLE 1 - AIR CARRIER ACCIDENT DATA

1964 THROUGH 1975

	ALL CAUSES	TIRE/WHEEL/BRAKE RELATED RTO's
ACCIDENTS	719	21
FATALITIES	2931	98
AIRCRAFT DESTROYED	120	5

Thus, approximately 3 to 4% of recent air carrier accidents, fatalities, and aircraft losses can be attributed to tire/wheel/brake related RTO's. Significantly, RTO accidents of this nature can probably be drastically reduced by measures proposed later in this analysis.

(2) To date, fatal RTO accidents have occurred on B-707 and DC-8 aircraft. The increased passenger capacity on current wide-body transports makes the potential for loss of lives in a fatal accident much more significant than some of the earlier jets. For example, in the B-747 RTO accident at Bombay, 392 passengers and crew were on board. All were successfully evacuated before the airplane was destroyed by fire. Reports indicate that flames reached the upper deck lounge while the flight crew was in process of doing the emergency checklist. As the last crewmember exited using an emergency descent device, the right main fuel tank exploded, engulfing the airplane in a huge fireball. Although the evacuation was successful in this case, it's not difficult to envision the potential for more serious results with slightly different circumstances.

(3) In addition to fewer fatalities, an improvement in the RTO safety record would precipitate considerable monetary savings. The exact magnitude of this is difficult to assess. Complete data is lacking, but some concept of the financial aspects can be gained from just the NTSB data utilized in this analysis. In 29 air carrier RTO accidents/incidents, 6 aircraft were destroyed, 9 aircraft sustained substantial damage, and most of the others sustained at least minor damage. When the costs which can accrue in RTO accidents (e.g.,tire, wheel, or brake replacement, structural repair, fire damage, FOD damage to engines, total aircraft destruction, medical costs, closed runways, loss of revenue, lawsuits, etc.) are considered, the amounts can be significant.

j. <u>RTO Test Procedures</u>:

In accordance with the stated objective of this study, and based on available accident and test data, an assessment of RTO test procedures is presented below. The results of this assessment have been incorporated in a proposed revision to the RTO test procedures in FAA Order 8110.8, Engineering Flight Test Guide for Transport Category Airplanes. The proposed revision is presently being staffed and reviewed. The primary benefit of this proposed revision will be to record and to standardize the RTO test procedures among the various FAA regions. It does not propose any drastic changes to the RTO test procedures at this time. There are, however, changes necessary as a result of this study. These changes must first be made in other regulatory mediums before being included in the RTO test procedures. If wet/slippery runway RTO accountability or other changes are subsequently required, appropriate revisions will be incorporated at a later date.

The major RTO test procedures of interest in this study are:

(1) Taxi

The question of whether or not an aircraft should be taxied with periodic stops to pre-heat brakes and tires prior to performing an RTO test is one characterized by a lack of test data. Certainly, in actual operations it is usual for some heat buildup to occur in tires and wheels prior to takeoff, although the degree may be quite variable, depending on conditions. However, there have been accidents in which prolonged taxi was a factor. An extreme case is that of a 727 (at Portland, Maine on 8/16/75) which taxied along the runway in an attempt to clear fog for takeoff. The prolonged taxi produced a wheel fire which substantially damaged the aircraft. In view of the fact that some degree of heat in tires/wheel/brakes can be expected in normal taxi operations, the procedure used by some applicants in towing an airplane to the takeoff point and allowing tires, wheels, and brakes to cool before performing an RTO demonstration is unrealistic and should not be permitted. A taxi distance of 2 miles with five stops immediately prior to the RTO demonstration appears realistic and is proposed as a new RTO test procedure.

(2) Worn Tires and Brakes

Tests have shown some degradation in stopping distance with partially worn tires. However, the amount of degradation is not significant enough to warrant conducting RTO tests with partially worn tires and/or brakes, provided the current policy of not accounting for reverse thrust is continued. The energy absorption capability of brakes can be expected to decline gradually as the surface contact material is worn away; however, there are no available data to show that this presents a significant problem with current wear limits and practices. Any loss in braking capability during operations due to partially worn tires or brakes tends to be offset by the conservatism built into current procedures by not permitting use of reverse thrust in RTO tests and Aircraft Flight Manual data but using reverse thrust in actual operations. Conducting RTO tests with worn tires or brakes would also present some problems in expense and achieving a consistent baseline for data measurement. Conducting tests with new tires and brakes lends itself more readily to achieving a consistent baseline and repeatable results. If subsequent analysis indicates that it is necessary to account specifically for the effect of worn tires and brakes in RTO tests, it may be better to conduct the

tests with new equipment and then apply a conservative factor to the data for the aircraft flight manual. It is not proposed, at this time, to account specifically for worn tires or brakes during RTO tests. The increase in stopping distance due to wet or slippery runways is a much more significant factor to consider.

(3) Failed Tires

(a) As previously noted, of the 171 RTO's analyzed in this study, 149 had some tire, wheel, or brake involvement. Of these, the 124 tire failures were by far the most significant cause or factor in the RTO's. Once a tire failure occurs, the RTO becomes especially critical because the additional load carrying capability or safety margin usually associated with most aircraft systems is not present in aircraft tires. Failure of a tire in an aircraft loaded at or near maximum gross weight shifts the load on the remaining tires and often results in failure of one or more remaining tires. This in turn applies even more load to the remaining tires, precipitating a progressively worsening situation. The situation is further aggravated due to design features of some modern anti-skid systems. The locked wheel protection feature of some anti-skid systems will relieve braking to paired wheels on one side of the aircraft if there is a significant loss of braking on the other side. Thus, a failed tire can result in a greater loss of braking capability than just that associated with the failed tire, and, in an RTO situation, at a time when it is most needed. The high percentage of tire failures in RTO accidents, the lack of significant safety margin in tire load carrying capability, and the progressive loss of braking capability associated with tire failures in RTO's make tires an especially critical item warranting special attention.

(b) In considering what action to take relative to the tire failure situation, the possibility of accounting for tire failures during RTO testing was considered. Although the maximum energy RTO's often result in tire failures, there is some question as to the feasibility of accounting for failed tires during all RTO testing. Even if it were feasible to account for failed tires and apply this data to the accelerate-stop charts in airplane flight manuals, this would unduly penalize payloads during day-to-day operations. It would certainly be more meaningful and positive to correct the basic cause of the problem than to

accommodate it by changing testing criteria and penalizing operations. It is therefore recommended that action be initiated to significantly reduce the incidence of tire failures during takeoffs or rejected takeoffs. This may entail improvements in maintenance, quality control, operating procedures, or tire strength and design standards, or a combination of these. The question of whether or not increased tire strength would permit unacceptable loads in the landing gear or supporting structure of existing airplanes is one which will probably require additional analysis or testing. The exact nature of the cure for tire failures is beyond the scope of this assessment; the need and priority for achieving a significant improvement is nonetheless important and urgent.

(4) Reverse Thrust Credit

FAR 25.109, Accelerate-Stop Distance, states that means other than wheel brakes may be used to determine accelerate-stop distance if that means

(a) is safe and reliable;

(b) is used so that consistent results can be expected under normal operating conditions; and

(c) is such that exceptional skill is not required to control the airplane.

The practice has been not to permit reverse thrust credit in determining accelerate-stop distances because present systems have not fully met the above criteria and reverse thrust provides the only safety margin for an engine-out RTO. This practice also tends to offset any loss in braking efficiency due to partially worn tires and brakes or failed tires. Current procedures associated with reduced thrust takeoffs, while still within current FAA criteria, tend to reduce the available safety margin in accelerate-stop distance. Also, some operators of wide-body jet transports have disconnected or removed part of the thrust reversing system on these aircraft, further reducing the stopping capability. All of these considerations constitute more than ample justification for continuing the current practice of not permitting reverse thrust credit in determining accelerate-stop distance. If reverse thrust credit is allowed at a later date, full accountability should be made in flight manual data and procedures for items not currently included, such as worn tires and brakes, failed tires, average airline pilot reaction times, and wet/slippery runways.

(5) Post RTO Procedures

Analysis of RTO accidents has not shown a need for revising the present Post-RTO Procedures. Present procedures in FAA Order 8110.8, Engineering Flight Test Guide for Transport Category Airplanes, state that following maximum energy RTO's, fires on or around the landing gear are acceptable if the fires can be allowed to burn for five minutes before extinguishers are required to maintain the safety of the airplane. The RTO is truly an emergency situation and considering the amount of energy which must be absorbed by the brakes in a maximum energy RTO, there is no practical way to avoid generating temperatures capable of providing an ignition source for tires, grease, hydraulic fluid, etc. The primary concern then becomes one of avoiding a fire which can jeopardize safety during evacuation of passengers and crew. In this regard, the present criterion is considered acceptable.

(6) Wet/Slippery Runway RTO Testing

RTO testing during airworthiness certification is usually accomplished on dry runways only, as there is presently no stated requirement for wet or slippery runway testing. Stopping distance on wet runways can be measured during certification, but in order to be meaningful during actual operations, the data must be related to runway conditions at the time of each takeoff at a specific airport. The stopping distance for wet runway RTO's varies widely under wet conditions depending on the type of runway material, surface texture, degree of contamination by rubber deposits, and water depth. Fortunately, an accurate and relatively inexpensive method has been developed to account for this. This method will be discussed in more detail later in the report.

Wet runway stopping distance data is available for some jet transport airplanes. It may be necessary to conduct tests on additional airplanes in order to account for most jet transport types currently in service.

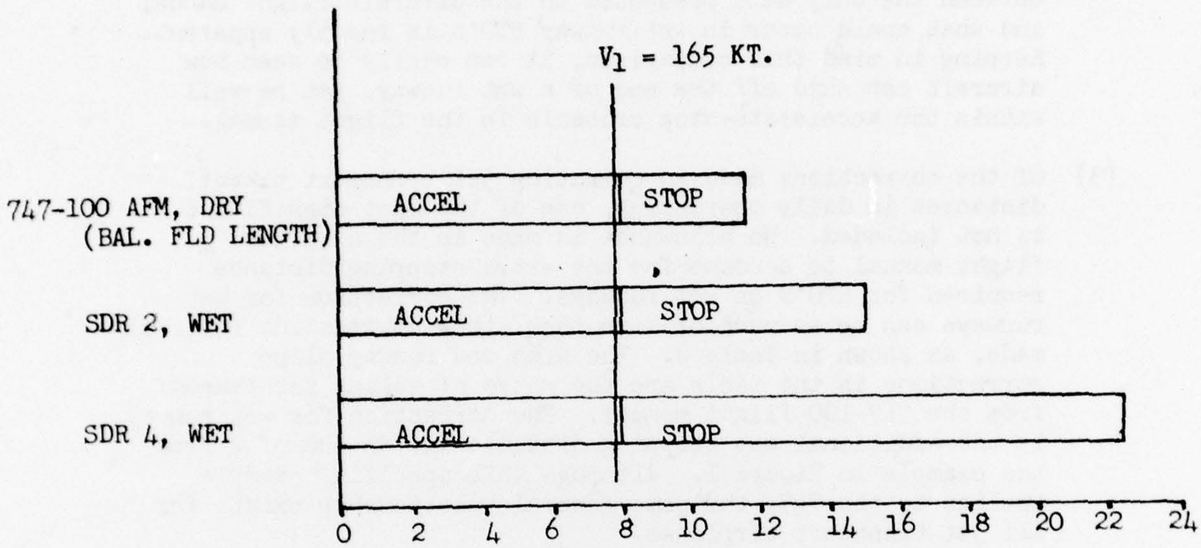
k. Wet/Slippery Runway Accountability

Probably the most important consideration arising from this RTO analysis is the need to provide an adequate level of safety in the event of an RTO on a wet or slippery runway. At present this is neither required nor addressed in the FAR's. The only safety margins are those resulting from the policy of not permitting reverse thrust during RTO certification and any wet/slippery runway criteria that manufacturers or operators may have provided of their own initiative. These are shown by accident data and analysis to be inadequate.

(1) Accidents (such as the previously mentioned 707 at Rome on 11/23/64 and the DC-10 at JFK International on 11/12/75) have documented that a takeoff can be aborted well below V_1 in accordance with approved criteria and procedures and yet the airplane can run off the end of a wet or slippery runway. If sufficient clearway exists for stopping the aircraft, this can result in nothing more than an unpleasant incident. But, if the airplane leaves the runway in an area of rough terrain or obstacles which can induce structural failure and subsequent fire, the results can be disastrous. At times, coefficients of friction on wet/slippery runways can be so low as to provide almost no stopping capability should it be necessary to reject a takeoff. The DC-8 accident at Anchorage, Alaska on 11/27/70 illustrates these extremely low runway friction conditions as does the case of the 747 at Anchorage on 12/16/75 in which the airplane was stopped with brakes applied, but blown off the taxiway and down an embankment by winds, sustaining substantial damage.

(2) Tests (References 1, 2, &3) have established that the stopping distance of jet transport aircraft is significantly greater on wet, ungrooved runways than on dry runways. These tests have also shown that the wet stopping distance varies widely depending on local runway characteristics and conditions such as the type of runway material, surface texture, degree of contamination by rubber deposits, and water depth on the runway. It thus becomes necessary in order to accurately account for stopping distance in wet runway RTO's to account for existing local conditions, just as local winds and runway slope are taken into consideration on each jet transport takeoff. A convenient means of expressing the difference in aircraft stopping distance on wet and dry runways is the Stopping Distance Ratio (SDR) which is simply a ratio of the airplane's measured wet-to-dry runway stopping distance. SDR values for some representative runways in the U.S. have been measured and the data are presented in Reference 4, and included in Appendix A to this report. These data show clearly the widely varying nature of the SDR at various locations. Values approaching 5 have been recorded with an average of approximately 2 for those measured. Figure 1 presents a comparison of accelerate-stop distances between aircraft flight manual (AFM) data and wet runways with SDR's of 2 and 4. Although the flight manual data is for a specific airplane, the same general relationship shown here applies for all jet transport airplanes.

FIGURE 1 - ACCELERATE - STOP DISTANCE COMPARISON



JT9D - 3A Engines

W = 680,000 Lb. (Max T.O. GR. WT. = 710,000 Lbs.)

Hp = 2000 ft.

OAT = 90°F

GRAD = +1%

Headwind = 10 kt.

10° Flaps

A/S Operative

A/C Pack On

In actual operations, the stop portion of these total distances could be reduced by the use of reverse thrust (to approximately 50 - 70% of the values shown), if full reverse thrust and braking are available. However, data shows that full stopping capability is not available in many RTO's due to worn or blown tires, malfunctions, etc. Even if reverse thrust is considered, the wide disparity between the only data presented in the aircraft flight manual and what could occur in wet runway RTO's is readily apparent. Keeping in mind this comparison, it can easily be seen how aircraft can skid off the end of a wet runway, yet be well within the accelerate-stop criteria in the flight manual.

(3) Of the corrections made in computing jet transport takeoff distances in daily operations, one of the most significant is not included. No allowance is made in the airplane flight manual to account for the extra stopping distance required for RTO's on wet runways. The correction for wet runways can be as much or more than other corrections routinely made, as shown in Table 2. The wind and runway slope corrections in the table are the range of values for takeoff from the 747-100 flight manual. The correction for wet runway is the additional wet stopping distance for an SDR of 2 from the example in Figure 1. Although this specific example applies to the 747, the same general relationship exists for all jet transport airplanes.

TABLE 2 - RUNWAY LENGTH CORRECTIONS

747-100 JT9D-3, All Engines, Flaps 10 & 20°

CONDITIONS	CORRECTION (Ft.)
10 kt. headwind	250 to 575
20 kt. headwind	500 to 1200
10 kt. tailwind	800 to 1850
runway slope +1%	100 to 1250
runway slope +2%	200 to 2400
runway slope -1%	50 to 1150
runway slope -2%	150 to 2050
correction for wet runway, SDR 2, no reverse thrust (Conditions as on Figure 1)	3700

(4) If the need is recognized to account for wet runways in takeoff (accelerate-stop) calculations, a viable and relatively inexpensive method exists for doing this. It is essentially the same as that proposed (Reference 1) for wet runway landings, and therefore has the added advantage of commonality. This method, in fact, is essentially that in use by Alaskan Airlines for wet/slippery runway landings. In this method, wet runway tests would be required for jet transports to establish basic reference data for use in the airplane flight manual. Takeoff data would be provided in the manual for a useable range of SDR's. The SDR at each air carrier runway can be conveniently determined by measurement with a DBV (Diagonal-Braked Vehicle), an automobile modified for accurate speed and distance measurement and braking on two diagonal wheels instead of all four. Periodic runway calibrations with the DBV would be required to account for changing conditions. Rain guages would be used to determine and account for water depth on the runway. It would not be necessary to measure SDR's each time it rained, provided valid calibrations are available, but measurements may be required for changing snow or ice conditions. With this approach an SDR for existing conditions could be computed and in conjunction with flight manual data, corrections to airplane weight or V_1 could be made to account for wet/slippery runways along with local winds, temperature, altitude, slope, etc. This method would not penalize operations on dry runways and would account for improvements such as runway grooving as they are made, yet would provide an adequate safety margin for RTO's on wet/slippery runways. It would, in fact, provide a much needed incentive for runway grooving, which has been shown (References 1, 2, &3) to offer significant improvement in wet runway stopping distance.

4. CONCLUSIONS:

a. The trend among jet transport aircraft toward heavier takeoff weights and higher takeoff speeds, as well as a number of serious RTO accidents involving tires, wheels, or brakes, have highlighted the critical nature of RTO's and prompted this analysis.

b. Of the 171 jet transport RTO's analyzed, 149 had some tire, wheel, or brake involvement, i.e. failures or malfunctions in these areas caused or were a contributing factor in initiating the RTO. Of these, tire failures were by far the major cause or factor accounting for 124 of these cases. The fact that most tire failures occur during takeoff underscores the critical role of tires during the RTO.

c. Wet or slippery runways are a significant factor in RTO accidents. Three of the five RTO accidents with fatalities or total aircraft destruction also involved wet or slippery runways.

d. Approximately 3 to 4% of air carrier accidents, fatalities, and aircraft losses can be attributed to tire/wheel/brake related RTO's. This includes 21 accidents, 98 fatalities, and 5 aircraft losses in an eleven year period. RTO accidents, fatalities, and aircraft losses of this nature can probably be drastically reduced by applying wet/slippery runway accountability and tire improvements.

e. The increased accelerate-stop distance necessitated by wet or slippery runways is not accounted for in current regulations or airplane flight manuals, allowing potential for further serious accidents.

f. In everyday jet transport operations, corrections to takeoff calculations are made for local conditions such as wind, runway slope, etc., yet these can be less significant than a correction for a wet/slippery runway which is needed but not currently required by applicable rules.

g. A viable, relatively inexpensive method for including wet/slippery runway accountability in takeoff has been developed, is compatible with the proposal for wet/slippery landing accountability, and would not penalize operations on dry runways or runways in which friction improvements, such as grooving, are incorporated.

5. RECOMMENDATIONS

It is recommended that:

a. Action be taken to significantly reduce the incidence of tire failures during takeoffs and rejected takeoffs. This may entail improvements in maintenance, quality control, operating procedures, tire strength or design standards, or a combination of these.

b. The increased accelerate-stop distance required on wet/slippery runways be taken into account in takeoff calculations and the necessary changes to airplane flight manuals, procedures, and regulations be incorporated to accommodate this.

REFERENCES

1. Leslie R. Merritt, Impact of Runway Traction on Possible Approaches to Certification and Operation of Jet Transport Aircraft, SAE Paper 740497, April 30, 1974.

2. Walter B. Horne, Thomas J. Yager, Robert K. Sleeper, Eunice G. Smith, and Leslie R. Merritt, Preliminary Test Results of the Joint FAA-USAF-NASA Runway Research Program, Part II: Traction Measurements of Several Runways Under Wet, Snow-Covered and Dry Conditions with a Douglas DC-9, a Diagonal Braked Vehicle and a Mu-Meter, NASA Langley Working Paper 1051, September 27, 1972.

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APPENDIX A

SUMMARY OF RESULTS - RUNWAY CALIBRATION

AIRPORT (DATE)	RUNWAY (MTL)	TARE (FT)	SLOPE (PCT)	TEST SECTION	DRY STOP (FT)	AVERAGE SDR	NORMAL SDR	TEXTURE DEPTH	AVG. H_2O DEPTH (IN)	MU METER
ALLENTOWN (9-2-75)	13/31 (GROOVED ASPHALT)		1.0	A	307.4	1.07	1.14	.0143	DAMP	
				B	307.6	1.08		.0105		
				C	307.9	1.29		.0108		
	6/24 (GROOVED ASPHALT)		0.75	A	312.9	1.71	1.79	.0160	DAMP	
				B	306.2	1.66		.0100	STAND. H_2O	
				C	301.5	2.07		.0125	"	
BOSTON (8-16-75)	4L/22R (GROOVED ASPHALT)		1.0	A	320.6	1.12	0.94		DAMP	
				B	390.8	0.90				
				C	362.3	1.00				
	4R/22L (GROOVED ASPHALT)		1.0	A	330.3	1.62	1.87			
				B	311.9	1.96				
				C	339.0	1.75				
	15R/33L (GROOVED ASPHALT)		1.0	A	302.8	1.39	2.00			
				B	350.9	2.00				
				C	313.8	2.50			DAMP	
BUFFALO (8-21-75)	14/32 (ASPHALT)		1.0	A	297.7	2.06	2.33	.0091	.033	
				B	295.9	2.30		.0091	.034	
				C	308.2	2.68		.0069	.043	
	5/23			A	(UNDER CONSTRUCTION)					
				B						
				C						
BURLINGTON (8-12-75)	15/33 (ASPHALT)		1.0	A	295.4	2.04	1.88	.0110	.020	
				B	298.7	1.75		.0220	.023	
				C	314.9	2.09		.0095	.022	
CHARLESTON (9-6-75)	5/23 (GROOVED CONCRETE)		0.80	A	294.7	1.27	1.35	.0083	DAMP	
				B	302.0	1.35		.0087	"	
				C	339.1	1.42		.0065	"	
	14/32			A	(UNDER CONSTRUCTION)					
				B						
				C						

APPENDIX A

SUMMARY OF RESULTS - RUNWAY CALIBRATION

AIRPORT (DATE)	RUNWAY (MTL)	TAKE (FT)	SLOPE (PCT)	TEST SECTION	DRY STOP (FT)	AVERAGE SDR	NORMAL SDR	TEXTURE DEPTH	AVG. H_2O DEPTH (IN)	MU FACTOR
DULLES (9-9-75)	1L/19R (CONCRETE)		1.0	A	313.7	3.90	3.27	.0044	.027	
				B	279.0	2.98		.0095	.022	
				C	288.7	3.11		.0055	.017	
	1R/19L (CONCRETE)		1.0	A	290.7	3.12	3.48	.0105	.040	
				B	279.1	3.13		.0095	.029	
				C	309.9	4.48		.0087	.039	
PHILADELPHIA (9-11-75)	9R/27L (ASPHALT)		1.0	A	312.3	4.39	3.44	.0053	.018	
				B	283.2	2.47		.0105	.016	
				C	312.3	3.57		.0053	.013	
	9L/27R			A	(NOT ACCOMPLISHED)					
				B						
				C						
PITTSBURGH (9-4-75)	10R/28L (GROOVED ASPHALT)		1.0	A	319.9	2.15	1.93	.0133	DAMP	
				B	332.7	1.63		.0167	"	
				C	345.0	2.54		.0143	STANDING	
	10L/28R (GROOVED CONCRETE)		1.5	A	327.1	1.43	1.39	.0143	DAMP	
				B	314.6	1.35		.0163	↓	
				C	301.4	1.49		.0174		
PORTLAND (8-13-75)	11/29 (ASPHALT)		1.0	A	320.0	1.54	1.36	.0286	.016	
				B	332.0	1.27		.0286	.012	
				C	352.8	1.41		.0302	.010	
	18/36 (ASPHALT)		1.0	A	318.0	1.86	1.82	.0100	.014	
				B	289.1	1.77		.0105	.008	
				C	290.0	1.83		.0111	.011	
ROCHESTER (8-19-75)	10/28 (ASPHALT)		1.0	A	307.8	2.18	1.89	.0070	.014	
				B	291.6	1.79		.0140	.021	
				C	285.1	1.74		.0220	.018	
	4/22 (CONCRETE)			A	284.7	3.68	3.85	.0040	.023	
				B	266.2	3.60		.0059	.021	
				C	271.8	4.50		.0054	.031	

APPENDIX A

SUMMARY OF RESULTS - RUNWAY CALIBRATION

AIRPORT (DATE)	RUNWAY (MTL)	TAKE (FT)	SLOPE (PCT)	TEST SECTION	DRY STOP (FT)	AVERAGE SDR	NORMAL SDR	TEXTURE DEPTH	AVG. H_2O DEPTH (IN)	MU METER
AKRON-CANTON (9-19-75)	1/19 (ASPHALT)		1.4	A	295.5	2.19	2.19	.0093	.010	
				B	297.1	2.01		.0117	.020	
				C	284.1	2.71		.0091	.025	
	5/23 (ASPHALT)		1.4	A	292.2	1.26	1.38	.0129	.025	
				B	296.1	1.47		.0129	.020	
				C	290.1	1.32		.0100	.020	
CINCINNATI (9-23-75)	18/36 (GROOVED ASPHALT)		1.5	A	312.1	1.51	1.87	.053	DAMP	
				B	301.6	2.05		.040		
				C	317.8	1.70		.050		
	9R/27L (GROOVED CONCRETE)		1.5	A	301.5	1.78	1.48	.050		
				B	284.7	1.38		.047		
				C	300.2	1.34		.033	DAMP	
CLEVELAND (9-17-75)	5R/23L (GROOVED ASPHALT)		1.3	A	307.4	2.40	2.09	.0105	.010	
				B	305.5	2.14		.0426	DAMP	
				C	317.4	1.70		.0286		
	10L/28R (GROOVED ASPHALT)		0.8	A	293.4	1.30	1.49	.044		
				B	303.0	1.57		.067		
				C	215.6	1.39		.0285	DAMP	
DETROIT (9-9-75)	3L/21R (GROOVED CONCRETE)		1.0	A	318.0	1.58	1.63	.050	DAMP	
				B	309.6	1.68		.050	DAMP	
				C	322.1	1.65		.250	DAMP	
	9/27 (ASPHALT/CONCRETE)		1.0	A^1	278.6	2.10	2.15	.0167	.020	
				B^2	294.7	1.91		.020	.020	
				C^3	313.5	2.77		.003	.030	
FT. WAYNE (9-6-75)	4/22 (CONCRETE/ASPHALT)		0.9	A^C	277.5	2.05	1.72	.0076	.020	
				B^A	289.2	1.55		.0210	.025	
				C^C	291.3	2.00		.0125	.010	
	9/27 (CONCRETE/ASPHALT)		–	A^C	292.6	1.77	1.80	.040	.025	
				B^A	278.8	1.80		.027	.020	
				C^C	283.6	1.81		.022	.020	

1 ASPHALT WITH A GROOVED CONCRETE PATCH
2 ASPHALT
3 CONCRETE

APPENDIX A

SUMMARY OF RESULTS - RUNWAY CALIBRATION

AIRPORT (DATE)	RUNWAY (MTL)	TAKE (FT)	SLOPE (PCT)	TEST SECTION	DRY STOP (FT)	AVERAGE SDR	NORMAL SDR	TEXTURE DEPTH	AVG. H_2O DEPTH (IN)	MU METER
GRAND RAPIDS (9-10-75)	8R/26L (ASPHALT/CONCRETE)		1.5	A[4]	308.3	1.96	1.77	.016	.010	
				B[4]	299.0	1.57		.031	.005	
				C[5]	291.8	2.36		.051	.010	
MADISON (8-18-75)	18/36 (CONCRETE)		1.5	A	284.1	1.35	1.47	.044	DAMP	
				B	286.5	1.43		.040		
				C	289.6	1.68		.027		
	13/31 (ASPHALT)		1.5	A	286.2	1.62	1.60	.008	.015	
				B	296.6	1.54		.008	.005	
				C	300.5	1.70		.008	.010	
MILWAUKEE (8-26-75)	1L/19R			A	(UNDER CONSTRUCTION)					
				B						
				C						
	7R/25L (CONCRETE)		1.0	A[6]	268.8	3.02/2.38	1.99/1.82	.044	DAMP/RAIN	
				B	268.3	1.56		.017	DAMP	
				C	271.3	1.67		.033	.010	
MOLINE (9-3-75)	9/27 (ASPHALT)		1.0	A	291.7	2.34	2.59	.020	.010	
				B	291.4	2.65		.020	.020	
				C	301.4	2.77		.004	DAMP	
	12/30 (CONCRETE)		1.0	A	288.6	2.66	2.60	.0085		
				B	293.9	2.49		.005	.015	
				C	305.0	2.91		.006	.015	
PEORIA (9-5-75)	12/30 (GROOVED ASPHALT)		1.25	A[4]	284.4	1.36	1.27	.014	DAMP	
				B[4]	294.5	1.16		.033	DAMP	
				C[5]	281.4	1.52		.015	.010	
	4/22 (ASPHALT)		1.0	A[4]	297.0	1.14	1.38	.025	DAMP	
				B	293.6	1.43		.050	.030	
				C	285.0	1.44		.012	.015	
				A						
				B						
				C						

6 ASPHALT PATCH
4 ALTERNATE GROOVING
5 NOT GROOVED